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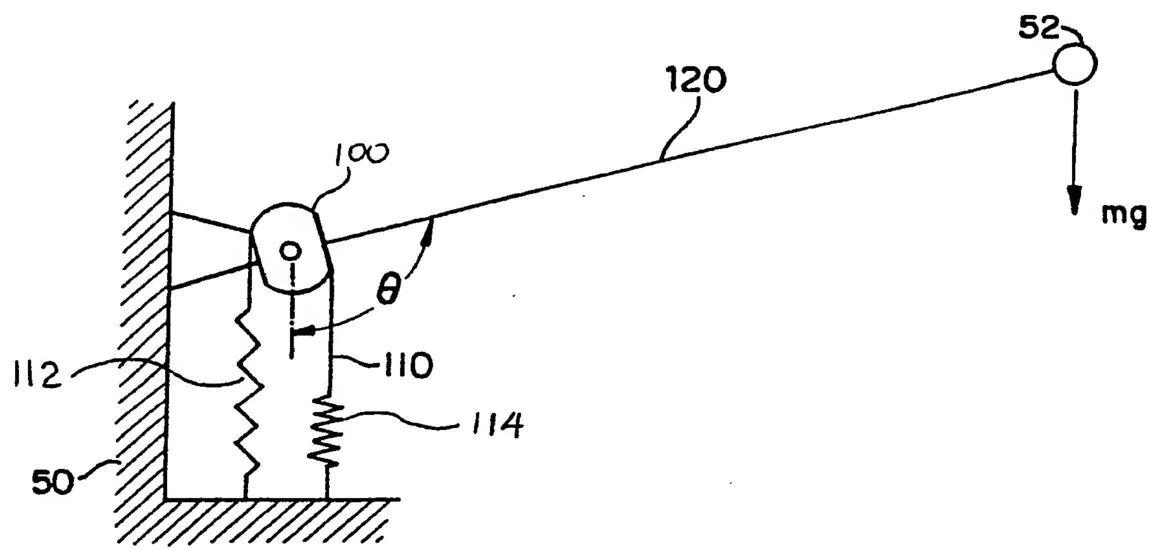

(57) Abstract

Methods and apparatus for compensating for the weight of an articulated manipulator are disclosed. Manipulators which use one or more links (120) connected in series by rotatable joints and which include tendons (112, 114) and cables (110) as part of the actuation system may be gravity compensated by providing an eccentric pulley (100) specially chosen to convert the linear force created by tendon tension into a non-linear resistive torque which counteracts the torque created by the weight of the apparatus throughout the range of motion. Simplified single link and generalized multiple link embodiments are disclosed. Methods of compensating for the effects of gravity are also disclosed.

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METHODS AND APPARATUS FOR PASSIVELY COMPENSATING FOR THE EFFECTS OF GRAVITY UPON ARTICULATED STRUCTURES

The present invention relates to articulated structures comprised of one or more links serially connected by rotatable joints. More specifically, the present invention relates to methods and apparatus for compensating for the effects of gravity acting upon an articulated structure undergoing manipulation.

BACKGROUND OF THE INVENTION

Articulated structures, including robotic manipulators, often comprise distinct members or "links" which are serially connected and manipulated by the activation of one or more rotatable joints which connect the links to a base, foundation or "platform." In many instances, the rotatable joints actuated by a cable or tendon. The human finger itself is a collection of serial links, connected at rotatable joints and activated by the force of tendons. In the field of robotics, a finger within this class is disclosed in U.S. Patent 4,957,320 which is assigned to the assignee of the present invention and is incorporated herein by reference. Other examples include the operative booms of cranes and other construction equipment and the structures which support X-ray equipment, television cameras, lamps, dental drills and a variety of other objects which must be moved through space.

One significant problem with designs of such apparatus is the large amount of actuator torque and energy used to compensate for gravity-induced joint loads. The gravity-induced joint loads referred to herein describe the loads placed upon a joint due to the weight of the manipulating apparatus itself, i.e., the mass of the links under the acceleration due to gravity. Because serial

linkages tend to propagate increasing forces back through the mechanism, gravity loading can, in many cases, account for more than 50% of the available actuator torque at the base links. Even in static configurations, large amounts of power can be consumed simply in resisting gravitational forces, with attendant decreases in available payload and efficiency.

The expressions relating gravity-induced joint torques and arm configuration as well understood and easily derived, but these relationships are non-linear and usually dependent on distal joint positions. Compensation for gravity-induced joint torque at the control level has a significant computational cost and increases power consumption, while decreasing manipulator performance. Clearly, the actuator power required to resist joint torques caused by the weight of links can be a significant problem. It would be desireable to provide a mechanical method to counteract gravity-induced joint torques, a technique which is passive, energy-conservative, and easily adapted to many kinematic configurations.

Designers have used numerous approaches in mechanical gravity compensation. One solution is to counterbalance the links and bring the center of mass coincident with the joint axis. Unfortunately, this solution increases the overall mass of the structure and thus its inertia, as well as requiring a method of adjustment to accommodate changing payloads. Active mechanical methods - hydraulic, pneumatic or electric - have also been described but these increase the power requirements and the complexity of the manipulation system. This type of system is disclosed, for example, by V.I. Adamor, V.P. Isyumskii, and v.E. Alimochkina, "Unloading of Arm Drives of a Jointed Industrial Robot, *Teoriya mekhanizmov i mashin* (34): 78-83 (1983) (Russian). A spring-linkage compensation system based on the familiar sine-generating mechanism has also been reported. Revin, E.I., "Mechanical Design of Robots" McGraw Hill (1988). Although passive and energy-conservative, the disclosed mechanism is not easily adapted to compact or multi-link

manipulator designs. The spring elements store gravitational potential as strain energy. An important consideration is to match the linear behavior of the spring with the non-linear variation in the gravitationally-induced joint torque.

Another common method of gravity compensation involves inclusion of the gravity-induced joint torque in the solution of the equations of motion, the subsequent provision of control compensation using the joint actuators. Aside from the additional computational complexity introduced, this solution results in degraded manipulator performance or necessitates larger actuators, transmissions, and structure. The power requirement is also concomitantly increased, since motor current is required to resist gravity, even in static configurations.

Therefore, it would be desireable to provide a gravity compensation system suitable for a variety of manipulator designs. Accordingly, it is an object of the present invention to provide a passive, energy conservative system which utilizes mechanical advantage rather than active control to achieve such gravity compensation.

It is a further object of the present invention to provide a gravity compensation system which may be readily applied and adapted to articulated structures comprising one or more joints.

Another object of the present invention is to present a system whereby multiple serial linkages which lie in more than one plane within an articulated member may be gravity compensated.

Finally, it is an object of the present invention to provide a class of articulated manipulators wherein the weight of the structure of the manipulator is compensated for so as to increase the versatility and payload of the manipulator.

SUMMARY OF THE INVENTION

These and other objectives are met by providing an articulated structure comprising a first link, a platform and a first rotatable joint connecting the proximal end of the first link and the platform, and comprising an eccentric pulley means and a compliant tendon means for resisting the rotation of the eccentric pulley. The compliant tendon is connected to the eccentric pulley to compensate for the force created by the weight of the link, thereby reducing the force required to move the distal end of the link through space. Preferably, the compliant tendon creates a force directly proportional to the change in its length and the pulley converts the force created by the tendon into a non-linear compensation torque which varies with the relative position of the link to effectively compensate for the force due to gravity. The magnitude of the non-linear compensation torque is the mathematical product of the payload, the length of the link and the cosine of the angle between the link and the vertical. In a preferred embodiment, the radius of the pulley varies as a function of angular displacement about the rotational axis of the pulley and the function which describes the radius of the pulley, $r_p(\theta)$, is:

$$r_p(\theta) = \sqrt{\frac{mgL}{k}\left(\frac{1}{4}\cos^2\frac{\theta}{2} + \sin^2\frac{\theta}{2}\right)}$$

In certain preferred embodiments, the present invention provides apparatus in which one or more links are connected in series by one or more joints; the axes of rotation of the joints are perpendicular to the direction of gravitational acceleration and pulleys and tendons are connected to at least one of the joints. The tendons are connected to the joint in tension and thus the force created by the pulley and tendon compensates for the force created by gravitational acceleration acting upon the links.

In other embodiments, the multiplicity of joints and the planes in which such joints lie results in apparatus comprising a plurality links connected in series by one or more rotational joints, wherein the torque produced at each joint is created by the relative position of the links and is described by the product of two or more joint angles by providing one or more pulley means and tendon means for actuating at least one of the joints. The pulley and tendon again compensate for the force created by gravitational acceleration acting upon the links. In such embodiments, the torque produced at one or more of the joints can be expressed as a function of the sum of two or more joint angles and the tendon and pulley provide a resistive force to compensate for the torque produced, the compensating force varying as a function of angular displacement of one or more of the joints. In any event, however, the compensating force created at each joint varies only with the angular displacement of the joint.

Methods of compensating for the effects of gravity are also disclosed.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a side elevational view of a simplified single link, single joint gravity compensated manipulator made in accordance with the present invention.

FIG. 2 illustrates the relationship between the effective radius of a pulley and the actual radius of a pulley.

FIG. 3 provides a comparison between an ideal gravity compensation eccentric pulley and a circular pulley.

FIG. 4 is a partially diagrammatic side view of a single link manipulator which can be gravity compensated in accordance with the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The principles of the present invention are preferably applied to manipulators or other articulated members which utilize cables or "tendons" to actuate one or

more of the joints between serially connected links. Those of ordinary skill will readily appreciate, as explained above, the manner in which such manipulators generally operate and the details of active and passive control of one or more joints by adjusting the tension of one or more tendons or otherwise causing the tendons to impart rotation upon pulleys. Thus, in a preferred embodiment the present invention is applied to manipulators which utilize tendon actuation as the source of manipulation for at least one joint.

Although roller chain, belt, and metal band transmissions are in common use in robots and other articulated structures, tendon or cable drives have recently gained popularity. The benefits of cable transmissions, which include increased efficiency, an improved ability to be backdriven, and better control behavior, have been demonstrated in manipulators such as the Whole-Arm Manipulator (WAM) developed at the Massachusetts Institute of Technology and the JASON underwater arm built at the Woods Hole Oceanographic Institution. The former of these is described in Townsend, W.T., "The Effect of Transmission Design on Force-Controlled Manipulator Performance" Ph.D. Thesis on file at the Massachusetts Institute of Technology, (April, 1988) and the latter in Salisbury et al., "Preliminary Design of a Whole-Arm Manipulation System (WAMS), Proceedings, IEEE Conference on Robotics and Automation (April, 1988). Additional advantages of this actuation method are presented herein.

Referring to FIG. 1, there is illustrated a single joint manipulator made in accordance with the present invention. An eccentric pulley 100 is rotatably attached to a platform or base 50. A compliant tendon 110 is passed over the pulley 100 and is also affixed to the platform 50. Extending from the joint attached to the pulley 100 is a link 120. The proximal end of the link is affixed to the pulley, while the distal end carries a payload 52. As shown by the arrow, the payload 52 creates a downward force "*mg*" equal in magnitude to its mass multiplied by the acceleration of

gravity and acting in the direction shown. The angular displacement of the link 120 about the axis of the pulley 100 is measured by the angle θ, as illustrated.

For the purposes of illustration and analysis the link 120 is assumed to be massless and infinitely stiff, with the payload 52 of mass m located at the endpoint a distance L from the axis of the rotational joint 100. In this case, the gravity-induced torque at the joint 100 can be expressed as:

$$T = - mgL \cos \theta$$

Ideally, a gravity-compensation method will exactly compensate for this torque without additional energy input. As explained below, the combination of a compliant tendon 110 and an eccentric pulley 100 can achieve this result.

A compliant tendon will generally act as a spring and create a resistive force generally directly proportional to the displacement of the member. The shape of the pulley 100 must translate this linear $F = - kx$ spring behavior to a non-linear compensation torque $T_{comp} = mgL \cos \theta$. This requires that:

$$mgL \cos \theta = Tr = - kxr$$

where T is the difference in tension between the two tendons, r is the effective radius of the pulley 100 (which is assumed to be symmetric such that the distance between the two tendons is 2r), the tendon 110 itself for purposes of illustration is shown in an embodiment including two springs 112,114; k is the spring constant associated with the two springs 112,114 and x is the linear displacement of the tendon 110. Differentiating the above equation with respect to θ yields:

$$-mgL \sin \theta = \frac{dT}{d\theta} r + \frac{dr}{d\theta} T$$

But by the principle of virtual work:

$$r d\theta = dx; \quad \frac{dT}{d\theta} = - kr$$

So, we get a different equation in r:

$$-kr^3 + mgL \sin\theta \frac{dr}{d\theta} + mgLr\cos\theta = 0$$

Which admits the solution:

$$r(\theta) = \frac{mgL}{k}\sin\theta$$

The above equation prescribes the necessary *effective* pulley radius for each angular displacement θ. However, as will be better understood with reference to FIG. 2, this does not describe the actual shape of the pulley 100 because the tendon 110 will leave the pulley 100 at the point P, which in general is not coincident with the point of intersection of the vector r with the cam profile of the eccentric pulley 100. Instead, a pulley shape must be designed with an actual radius of $r_p(\theta)$ at an angular displacement $\phi(\theta)$ from r. This can be expressed as:

$$r_p(\theta) = \sqrt{\frac{mgL}{k}\ \frac{1}{4}\cos^2\frac{\theta}{2} + \sin^2\frac{\theta}{2}}$$

$$\phi(\theta) = \tan^{-1}\left[\frac{1}{2}\cot\frac{\theta}{2}\right]$$

As illustrated by FIG. 3, the actual shape of an eccentric pulley 100 made in accordance with this equation may be compared to the profile of a circular pulley, shown in phantom. Surprisingly, the profiles are identical to within 1.5% over a range of 180° of the perimeter.

In order to test this method of gravity compensation, a single-joint system similar to that illustrated in FIG. 1 was built. This cam profile shown in FIG. 3 was used on a cable pulley with an effective rotational range of 240°. By using highly accurate computer numerically controlled (CNC) milling machinery, the shape was manufactured with a base radius of 20 mm and with a maximum error of less

than 12 μ. An arm 200 mm long and which induces a maximum gravitational torque of 1 N-m was compensated for using these pulleys and springs with spring constants of approximately 670 N/m. The base pivot was supported by ball bearings. The static frictional torque of the system was determined to be 0.039 N-m, or less than 5% of the maximum gravitational torque.

In fixed positions, the compensation exactly counteracted the gravitational force acting upon the arm, with no resultant motion. A mass counterbalancing system on the arm allowed fine adjustment, and by testing the behavior of the system during motion, with the lower dynamic friction associated with rolling-element bearings, the compensation was tuned. The resulting behavior was identical to that of a mass counterbalanced arm, except that the inertia of the system was significantly less.

The theoretical calculations, proven by experience, set forth above in relation to FIG. 1, lead to a generalized case whereby the gravity compensation system of the present invention may be applied to a wide range of manipulators. The equations of motion for an unloaded n-link manipulator can be expressed in matrix form as:

$$\tau - I\theta + f(\theta,\theta) + G = 0$$

where the gravity term G consists, in general, of highly non-linear terms dependent upon joint angles. Although it is theoretically possible to use the n joint displacements as inputs to a mechanical compensation scheme which yields n joint torques as outputs, this is not a trivial problem for many kinematic configurations. To illustrate the application of the gravity-compensation method of the present invention to specific manipulators exemplary constructions of further preferred embodiments are helpful.

Referring now to FIG. 4, there is illustrated a partially diagrammatic representation of a portion of a robotic manipulator to which the gravity compensation system of the present invention may be applied. Gravity compensation as defined above for a single-link arm can be easily extended

to multiple links when the joint axes remain perpendicular to the direction of gravitational acceleration. The so-called "elbow" manipulator, of which the Puma series built by Unimation Corporation (USA) is a common example, has just this type of configuration.

Consider a free-body diagram of one link in such a kinematic chain, as shown in FIG. 4. The proximal joint 200 of this link 220 is actuated by tendons 210 parallel to a line connecting this joint axis with the previous joint axis (not shown) and with tensions T_1 and T_2. A payload weight 52 m_j+1 g is supported at the distal end. In addition, the link has a mass m_{jg} and a center of mass located a distance $L_{cm,j}$ from the proximal joint axis. The reaction force at the proximal joint bearings can be decomposed into components perpendicular and parallel to the previous link, represented by the arrows R_p and R_N shown in FIG. 4.

The tensions in the tendons 210 and reaction force R_P are resisted by the structure of the previous link (not shown). The only reaction force which affects the torque around the previous joint is R_N, such that the gravity torque at the (j - 1)th joint is:

$$\tau_{j-1} = m_{j-1}gL_{cm,j-1}cos\ \theta_{j-1} + RNL_{j-1}$$

with quantities defined as in the jth link. But static equilibrium requires:

$$R_N = (m_j + m_{j+1})\ \ g\ \cos\theta_{\ j-1}$$

and the equation becomes:

$$\tau_{j-1} = m_{j-1}\ gL_{cm,j-1}\ \cos\theta_{j-1} + (m_1 + m_{j+1})\ gL_{j-1}\ \cos\ \theta_{j-1}$$

which is only dependent upon θ_{j-1}, as the same analysis can be extended for all other joints in a system. The gravitationally-induced torque at each joint varies only with its displacement, and not with distal joint positions.

Those of ordinary skill will appreciate that this is a significant result. For kinematic configurations where a series of joints remains perpendicular to the direction of gravitational acceleration, each joint may be independently compensated for the effects of gravity using the same method that was derived earlier for a single joint such as that

illustrated in FIG. 1, where the mass of all distal links is assumed to be concentrated at the outboard joint axis. This behavior occurs when joints are actuated by tension elements and cables routed to the base frame. Of course, this has further significance from a kinematic, dynamic, and control standpoint, the impact of which will be readily apprehended by those of ordinary skill.

Additionally, the present invention finds applicability in manipulator systems beyond the single joint and "elbow" configurations described above in relation to FIGS. 1 and 2 respectively. However, these other kinematic configurations require more complicated approaches. For example, a kinematic skeleton for an arm can be envisioned which has similar degrees of freedom as are found in the human arm. The arm illustrated is a generalized representations of the arm known as the "MIT/WAN" arm, disclosed in Salisbury, J.K. et al. "Preliminary Design of a Whole-Arm Manipulator System (WAMS). Proceedings, IEEE International Conference on Robotics and Automation (April, 1988). The arm is comprised of the three joints and also provides a further axis of rotation along the longitudinal axis of one of the links. The gravity-induced torques at each of the joints are:

$$\tau_0 = 0$$

$$\tau_1 = (m_3 g L_1 + m_1 g L_{cm1}) \cos \theta_1$$

$$\tau_2 = (m_3 g L_{cm3} \cos \theta_1 + \theta_3) \cos \theta_2$$

$$\tau_3 = m_3 g Lcm_3 \cos (\theta 1 + \theta_3) \cos \theta_2$$

Unfortunately, τ_2 and τ_3 involve products of several joint angles and cannot be compensated for using the simple method described earlier. However, by the use of trigonometric identifies, we can express them as cosine functions of various sums of joint angles:

$$\tau_2 = \frac{1}{4} m_3 g L_{cm3} [\cos (\theta_2 + \theta_3) + \cos (\theta_1 + \theta_2 - \theta_3)$$
$$- \cos (\theta_1 - \theta_2 - \theta_3) - \cos (\theta_1 + \theta_2 + \theta_3)]$$

$$\tau_3 = \frac{1}{2} m_3 g L_{cm3} \left[\cos(\theta_1 - \theta_2 + \theta_3) + \cos(\theta_1 + \theta_2 \ \theta_3)\right]$$

It is straightforward to construct a pulley and tendon system which has as its inputs the joint displacements and as its output a sum of these, and which would allow compliant tendon and pulley compensation as described above.

The torques induced by gravity at each joint can be determined for any kinematic configuration. In general, they will be expressions which involve trigonometric functions of several joint displacements. Although it is theoretically possible to synthesize a mechanical calculator which will allow the application of the gravity compensation method described here, whether the resulting complexity is justified upon the application.

The present invention thus provides simple mechanical method for passively compensating for gravitationally-induced joint torques. The methods and apparatus can be easily applied to specific kinematic configurations. Other manipulator designs require more complicated approaches. A single-joint embodiment has been constructed and proven that the methods disclosed herein are effective.

The present invention discloses a unique manner in which the linear function of spring force may be converted to a force curve varying according to a sine function, which accurately compensates for the varying loading which a force being manipulated by a link connected to a rotating joint exerts. Theoretical equations provide a model system which permits an idealized eccentric pulley profile to be designed. As will be appreciated by those of ordinary skill, the present invention provides an efficient mechanism whereby the effective payload of a manipulator can be increased. By substantially removing the weight of the manipulator arm itself, the effects of this force upon the overal system is reduced. In conventional robotic manipulators, up to 70% of the maximum useful torque is required merely to hold the

manipulator in certain positions. The need for this torque is substantially eliminated using the present invention since the weight of the manipulator arm itself does not act through one of the joints. The use of the present invention will also improve the dynamic performance of manipulators since inertial effects due to the weight of the links may be substantially reduced, since the actuators and motors can be made smaller, permitting greater speed and precision.

The present invention will be preferably applied to those manipulators in which the torque required to drive the joints is a limiting factor, or where the lower efficiency of utilization of the power input to the joints is a problem. Moreover, since the present invention permits smaller and less expensive drive mechanisms and actuators to be used, both the cost of the manipulator apparatus itself and the expenses related to its operation are reduced.

Although certain embodiments of the present invention have been described in detail, these examples are for purposes of illustration and are not meant to be limiting. Upon review of the derivations and generalized equations associated therewith, those of ordinary skill will realize that numerous modifications and adaptations of the principles set forth herein are possible and entirely practical. Accordingly, reference should be made to the appended claims in order to determine the scope of the present invention.

WHAT IS CLAIMED IS:

1. An articulated structure, comprising:

at least a first link having a distal and a proximal end;

a platform; and

a first rotatable joint connecting the proximal end of the first link and the platform, and comprising an eccentric pulley means and a compliant tendon means for resisting the rotation of the eccentric pulley,

whereby the compliant tendon is connected to the eccentric pulley to compensate for the force created by the weight of the link, thereby reducing the force required to move the distal end of the link through space.

2. The apparatus of claim 1, wherein the compliant tendon creates a force directly proportional to the change in its length and the pulley converts the force created by the tendon into a non-linear compensation torque which varies with the relative position of the link to effectively compensate for the force due to gravity.

3. The apparatus of claim 2, wherein magnitude of the non-linear compensation torque is the mathematical product of the payload, the length of the link and the cosine of the angle between the link and the horizontal.

4. The apparatus of claim 1, wherein the radius of the pulley varies as a function of angular displacement from the horizontal about the rotational axis of the pulley.

5. The apparatus of claim 4, wherein the function which describes the radius of the pulley is:

$$r_p(\theta) = \sqrt{\frac{mgL}{k} \frac{1}{4} \cos^2 \frac{\theta}{2} \sin^2 \frac{\theta}{2}}$$

6. Apparatus comprising:

one or more links connected in series by one or more joints, wherein the axes of rotation of the joints are perpendicular to the direction of gravitational acceleration;

one or more pulley means and tendon means connected to at least one of the joints, the tendons being connected to the joint in tension,

whereby the pulley means and tendon means compensate for the force created by gravitational acceleration acting upon the links.

7. The apparatus of claim 6 wherein the compensating force created at each joint varies only with the angular displacement of the joint.

8. The apparatus of claim 7 wherein at least one of the pulleys is an eccentric pulley.

9. The apparatus of claim 7 wherein at least one of the tendons is a compliant tendon.

10. Apparatus comprising:

a plurality links connected in series by one or more rotational joints, wherein the torque produced at each joint is created by the relative position of the links and is described by the product of two or more joint angles;

one or more pulley means and tendon means for actuating at least one of the joints, the tendons being connected to the joint in tension,

whereby the pulley means and tendon means compensate for the force created by gravitational acceleration acting upon the links.

11. The apparatus of claim 10 wherein the torque produced at one or more of the joints can be expressed as a function of the sum of two or more joint angles and the tendon and pulley provide a resistive force to compensate for the torque produced, the compensating force varying as a function of angular displacement of one or more of the joints.

12. The apparatus of claim 11 wherein at least one of the pulleys is an eccentric pulley.

13. The apparatus of claim 11 wherein at least one of the tendons is a compliant tendon.

14. Apparatus for manipulating an object comprising a link means for holding the object;

a rotatable joint connecting the link and a platform means;

compliant tendon means for connected to the rotatable joint which creates a force directly proportional to the length it is displaced; and

eccentric pulley means connecting the rotatable joint and the compliant tendon means,

whereby the torque created by the weight of the link is compensated over the range of motion of the apparatus by the force created by the tendon passing over the eccentric pulley.

15. A method of compensating for the effect of gravity upon an articulated structure comprising the steps of:

providing an articulated structure having at least one rotatable joint activated by a pully and a compliant tendon;

choosing the pulley to have a shape whereby the rotation of the pulley converts the force of the compliant tendon into a compensation force equal to the weight of the structure in a particular orientation.

AMENDED CLAIMS
[received by the International Bureau on 9 March 1992 (09.03.92) ; original claims 1, 2, 4, 14 and 15 amended ; other claims unchanged (3 pages)]

1. An articulated structure, comprising:

at least a first link having a distal and a proximal end;

a platform;

a first rotatable joint connecting the proximal end of the first link and the platform, the joint comprising a variable radius eccentric non-circular pulley having a rotational center as a non-circular profile defined by a variable radius; and

a compliant tendon means for resisting the rotation of the eccentric pulley connected to the platform,

whereby the compliant tendon means is coupled with the eccentric pulley and creates a force to compensate for the force created by the weight of the link, thereby reducing the force required to move the distal end of the link through space.

2. The apparatus of claim 1, wherein the compliant tendon means creates a force directly proportional to the change in its length and the pulley converts the force created by the compliant tendon means into a non-linear compensation torque which varies with the relative position of the link to effectively compensate for the force due to gravity which acts upon the link.

4. The apparatus of claim 1, wherein the variable radius of the pulley varies as a function of angular displacement about the rotational axis of the pulley.

10. Apparatus comprising:

a plurality links connected in series by one or more rotational joints, wherein the torque produced at each joint is created by the relative position of the links and is described by the product of two or more joint angles;

one or more pulley means and tendon means for actuating at least one of the joints, the tendons being connected to the joint in tension,

whereby the pulley means and tendon means compensate for the force created by gravitational acceleration acting upon the links.

11. The apparatus of claim 10 wherein the torque produced at one or more of the joints can be expressed as a function of the sum of two or more joint angles and the tendon and pulley provide a resistive force to compensate for the torque produced, the compensating force varying as a function of angular displacement of one or more of the joints.

12. The apparatus of claim 11 wherein at least one of the pulleys is an eccentric pulley.

13. The apparatus of claim 11 wherein at least one of the tendons is a compliant tendon.

14. Apparatus for manipulating an object comprising:

a link;

a platform;

a rotatable joint connecting the link and the platform;

compliant tendon means connected to the rotatable joint which creates a force directly proportional to the length it is displaced; and

variable radius eccentric pulley means having an axis of rotation at the center of the eccentric

pulley means coincident with the rotatable joint and coupled with the compliant tendon means,

whereby the torque created by the weight of the link is compensated over the range of motion of the apparatus by the force created by the tendon passing over the eccentric pulley.

15. A method of compensating for the effect of gravity upon an articulated structure comprising the steps of:

providing an articulated structure having at least one rotatable joint activated by a pulley and a compliant tendon;

choosing the pulley to have a shape whereby the rotation of the pulley converts the force of the compliant tendon into a compensation force equal to the weight of the structure in a particular orientation.

STATEMENT UNDER ARTICLE 19

The following original claims are unchanged:

6 through 13 and 15. Claims 1, 2, 4 and 14 have been amended; claims 3 and 5 have been cancelled.

The differences between original claims 1, 2, 4 and 14 are as follows:

Claims 1 and 14 have been amended to more particularly define the shape of the pulley as having a variable radius, non-circular profile and also defining the structural relationships between the components and the forces they generate. Support for these limitations is found, for example, at p. 4, lines 18-19.

Claim 2 has been amended to define the tendon as being the compliant tendon defined in claim 1.

Claim 4 has been amended to identify the pulley as being the pulley defined in claim 1 and the term "displacement from the horizontal" has been changed to "displacement about the rotational axis."

Applicants request that the application be considered with such amendments and that a speedy and favorable response be forthcoming.

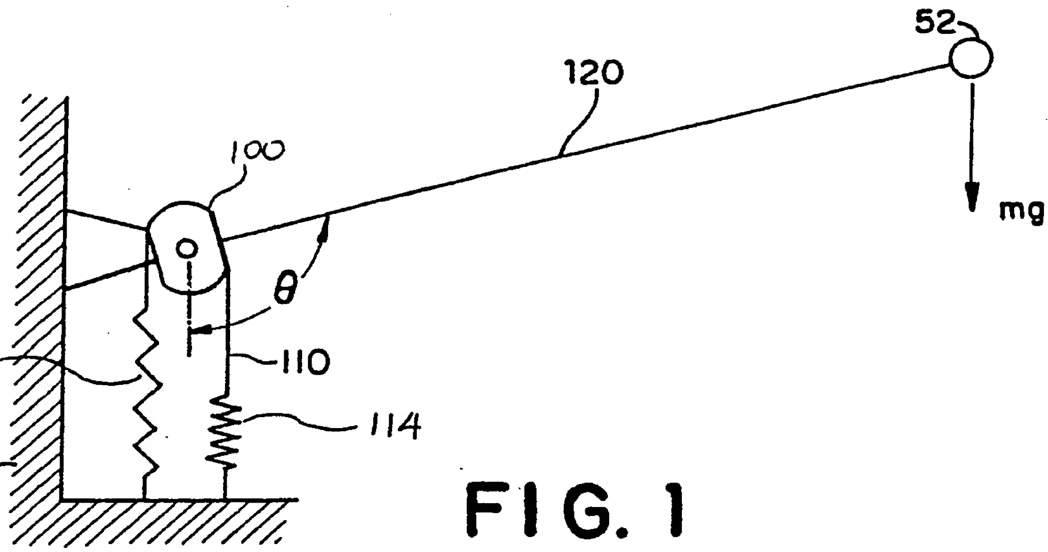

FIG. 1

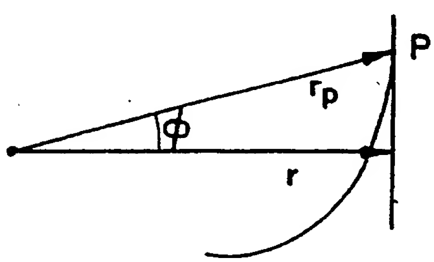

FIG. 2

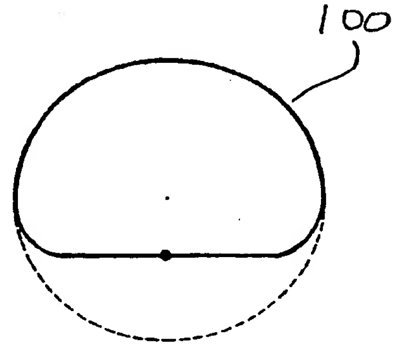

FIG. 3

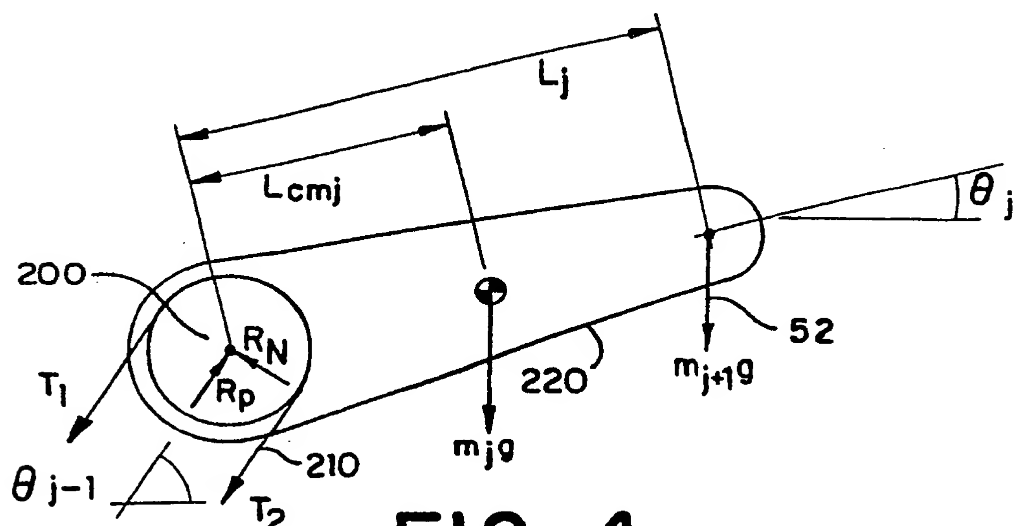

FIG. 4

INTERNATIONAL SEARCH REPORT

International Application No. PCT/US91/06679

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [6]

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC(5): B25J 19/00
US: 414/719 901/48

II. FIELDS SEARCHED

Minimum Documentation Searched [7]

Classification System	Classification Symbols
U.S. CL.	414/719,720 901/21,48

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [9]

Category *	Citation of Document, [11] with indication, where appropriate, of the relevant passages [12]	Relevant to Claim No. [13]
X	EP, A, 0,316,531 (YOSHIDA) 24 MAY 1989 See Figure 1	1-4,14,15
X	SU, A, 1,458,216 (SMOLENSK) 15 FEBRUARY 1989 See Figure 1	1-4,14,15
A	SU, A, 1,426,782 (MOMA) 03 MARCH 1987	
A	DL, A, 0,219,427 (KROMER) 02 DECEMBER 1983	
A	DL, A, 0,200,370 (ROBOTRON) 20 APRIL 1983	
A	SU, A, 0,480,538 (FORGING) 18 DECEMBER 1975	
A	US, A, 4,784,010 (WOOD ET. AL.) 15 NOVEMBER 1988	
A	US, A, 4,500,251 (KIRYU ET. AL.) 19 FEBRUARY 1985	

* Special categories of cited documents: [10]

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
17 DECEMBER 1991	10 JAN 1992
International Searching Authority	**Signature of Authorized Officer**
RO/US	Andre Robinson ROBERT J. SPAR

Form PCT/ISA/210 (second sheet) (Rev.11-87)

International Application No. PCT/US91/06679

FURTHER INFORMATION CONTINUED FROM THE SECOND SHEET

V. [ ] OBSERVATIONS WHERE CERTAIN CLAIMS WERE FOUND UNSEARCHABLE [1]

This international search report has not been established in respect of certain claims under Article 17(2) (a) for the following reasons:

1. [ ] Claim numbers ______, because they relate to subject matter [12] not required to be searched by this Authority, namely:

2. [ ] Claim numbers ______, because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out [13], specifically:

3. [ ] Claim numbers ______, because they are dependent claims not drafted in accordance with the second and third sentences of PCT Rule 6.4(a).

VI. [X] OBSERVATIONS WHERE UNITY OF INVENTION IS LACKING [2]

This International Searching Authority found multiple inventions in this international application as follows:

Group I: Claims 1-5, 14 and 15
Group II: Claims 6-13

1. [ ] As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims of the international application.

2. [ ] As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims of the international application for which fees were paid, specifically claims:

3. [X] No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claim numbers:

1-5, 14-15

4. [ ] As all searchable claims could be searched without effort justifying an additional fee, the International Searching Authority did not invite payment of any additional fee.

Remark on Protest

[ ] The additional search fees were accompanied by applicant's protest.

[ ] No protest accompanied the payment of additional search fees.

Form PCT/ISA/210 (supplemental sheet (2)) (Rev. 11-87)